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Feedback Processes: A Theoretical Perspective

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Abstract. I review the evidence for the importance of feedback from massive stars at small and large scales. The feedback mechanisms include accretion luminosity, ionizing radiation, collimated outflows, and stellar winds. The good news is that feedback doesn't entirely prevent the formation of massive stars, while the bad news is that we don't know what does limit their masses. Feedback from massive stars also influences their surroundings. I argue that this does not produce a triggering efficiency above unity, nor does it prevent lots of prompt star formation in GMCs, though it may preserve massive remnants of the clouds for many dynamical times.

1. Small Scale Feedback and the Upper Mass Limit

Massive stars influence their surroundings through a wide variety of feedback mechanisms. Their ionizing radiation (e.g., Vacca, Garmany, & Shull 1996) and line-driven winds (Castor, Abbott, & Klein 1975) have been known for many years, while only more recently have collimated jets and wide-angle outflows been observed from young, massive stars (e.g., Beuther & Shepherd 2005).

The initial mass function for stars above a solar mass or so follows a power law with slope -2.35 (Salpeter 1955) up to an upper cutoff mass of $m_{up} \sim 100 M_{\odot}$ (Figer 2005). The two most favored ideas currently for what determines the slope of the IMF are turbulent fragmentation of the parent cloud (Padoan et al. 2007) or competitive accretion (Bonnell & Bate 2006). What determines the value of the cutoff mass m_{up} remains unknown. Limitation of accretion by increasingly strong feedback in increasingly massive stars remains a viable candidate mechanism (Zinnecker & Yorke 2007).

In fact, the limitation of accretion by radiative feedback had long been a severe problem in theories of massive star formation, because in models of spherically symmetric accretion, radiation pressure on standard interstellar dust prevents accretion on to stars with mass $M > 30 M_{\odot}$ (Wolfire & Cassinelli 1987). However, recent models have called this conclusion into question because of better treatment of dust properties, non-spherical accretion, and the high accretion rates expected in high pressure cores (e.g., McKee & Tan 2003) such as those that have been identified by the *Midcourse Space Experiment* and *Spitzer Space Telescope* (Shirley et al. 2003).

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Yorke & Sonnhalter (2002) performed two-dimensional, nested-grid, numerical models of the collapse of slowly rotating, unmagnetized, molecular cores, using a wavelength-dependent treatment of dust grain properties for a mixture of small amorphous carbon grains, astrophysical silicates, and, in colder regions, water and ammonia ice coatings. They found that a combination of decreased opacity, disk accretion, and focusing of radiative losses through the polar cavity (the “flashlight effect” first discussed by Yorke & Bodenheimer 1999) allowed formation of 35–45 M_{\odot} stars. Krumholz, McKee & Klein (2005a) used computations of radiative transfer to demonstrate that the flashlight effect can be further enhanced if a collimated gas outflow clears a cavity in the envelope.

The efficacy of radiation in preventing accretion is further reduced by two other effects. First, Krumholz, Klein & McKee (2005) showed that in three dimensions, the radiation-driven bubbles that form when the radiation pressure begins to repel gas are subject to Rayleigh-Taylor instability. Essentially, the radiation acts as a light fluid that is trying to support the heavy gas. As a result, the bubbles tend to collapse, allowing additional accretion. Second, in a magnetized core, the photon bubble instability (Arons 1992) can also act to allow radiation to escape (Turner, Quataert, & Yorke 2007). This occurs when compressive MHD waves are amplified by radiation pressure, forming low-density regions into which the radiation streams.

Although radiation does not prevent accretion entirely, it does heat the surrounding core once a protostellar object has formed in the center. The luminosity from accretion onto even a sub-solar mass protostar can heat the surrounding envelope enough to prevent fragmentation during the collapse of a centrally condensed core (Krumholz 2006). Adaptive mesh refinement simulations including radiative transfer using a temperature dependent opacity show that fragmentation is strongly suppressed when compared to models with an isothermal equation of state (Krumholz, Klein & McKee 2007). At the time of publication, these models had only reached 10 M_{\odot} , but more recent conference reports have not yet given an upper mass limit. Although this work calls into question the competitive accretion scenario (Krumholz, McKee & Klein 2005b), it remains to be seen whether the two scenarios converge to a common description of collapse when beginning from a turbulent cloud rather than a centrally condensed core (see Clark or Bonnell in this volume).

The good news here is that we seem to understand why feedback does not entirely prevent massive star formation. The bad news is that we still don’t know if it does or does not ultimately determine the upper mass limit of around 100–150 M_{\odot} (e.g., Figer 2005). Several alternate explanations can be imagined. For example, if fragmentation cannot be prevented for cores above the upper mass limit (perhaps because of insufficient central radiative heating), then the upper mass limit would be determined by the largest mass reservoirs available. Alternatively, disk fragmentation could cut off accretion around too massive stars. Another suggestion is that massive stars grow by direct collision, so that the stellar density is the limiting factor.

If feedback does act to cut off accretion, which mechanism is dominant? Jets and winds appear to evolve during the formation of massive stars. Beuther & Shepherd (2005) suggest an evolutionary sequence in which the outflow type evolves as the central star accretes additional mass. In this sequence, high mass protostellar

objects with central stars appearing as mid-to-early B stars have strongly collimated jets, early B to late O stars that have already formed hypercompact H II regions start to show a line-driven wind in addition to the jet, while early O stars that have accreted most or all of their mass and have ultracompact H II regions (UCHRs) lose the jet and retain only the wind. This sequence could be symptomatic of disk destruction and accretion cutoff in the final stages, a hypothesis supported by the lack of observation of O stars with collimated jets (Shepherd, Test, & Stark 2003; Sollins & Megeath 2004; Arce et al. 2007) or disks (Cesaroni et al. 2007). Whether the winds themselves can destroy the disks remains an open question, however.

Jets have been suggested by Nakamura & Li (2007) as a way of supporting cluster-forming cores. However, the relatively low-resolution numerical models they used do not yet resolve the question of whether the turbulence driven in the cluster can actually cut off accretion. Furthermore, their outflow-driven turbulence model predicts a prominent break in the kinetic energy power spectrum at a scale close to the outflow length. Such a break has not yet been observed in a molecular cloud. For example, Ossenkopf & Mac Low (2002) found no break in the Polaris Flare—admittedly not a cluster forming core. Banerjee et al. (2007) examine the velocity distribution produced by a single Mach 5 jet and find very little supersonic material outside the head of the jet, suggesting that jets may have difficulty driving the observed supersonic turbulence in clouds. On the other hand, Matzner (2007) offers an analytic treatment that argues that jets can indeed drive the observed turbulence, consistent with Nakamura & Li (2007).

Ionizing radiation from the growing central star offers another mechanism for cutting off accretion. Keto (2002b) made the important point that the formation of an H II region around a massive star does not cut off accretion until the Strömgren radius grows to beyond the Bondi-Parker radius where the sound speed in the ionized gas exceeds the local escape velocity. Keto (2007) semi-analytically predicted the evolutionary sequence for stars forming in rotating, collapsing, cores, using the similarity solution derived by Terebey et al. (1984). A gravitationally confined, quasi-spherical, hypercompact H II region forms first, which then transforms to a bipolar UCHR as accretion increases the central star’s mass and luminosity. As the ionizing luminosity increases further, only a remnant disk remains neutral, and finally that evaporates as well. The basic prediction of this model that hypercompact H II regions should show evidence of accreting ionized gas has been borne out by observations both by Keto (2002a); Keto & Wood (2006) and by others (Beltrán et al. 2006).

If ionizing radiation is to cut off accretion, the final stage of accretion will be through a photoevaporating disk. This configuration was first analytically described by Hollenbach et al. (1994) in the context of solar mass star formation, while in the context of massive stars an analytic treatment of the structure of the photoevaporating wind was done by Lugo, Lizano, & Garay (2004). The best numerical model to date was done by Richling & Yorke (1997) using a two-dimensional radiation gas dynamics code that included an explicit treatment of dust scattering. Dust scattering leads to a factor of 3–4 increase in the photoevaporation mass loss rate, which they show to be proportional to the stellar luminosity $S_*^{0.58}$, close to the analytic prediction of Hollenbach et al. (1994),

though flattening somewhat at photon luminosities $S_* > 10^{47} \text{ s}^{-1}$. They also explicitly included line-driven stellar winds in some models, demonstrating that they were collimated by the disk and photoevaporating wind.

If UCHRs expand at the sound speed of ionized gas, $c_i \sim 10 \text{ km s}^{-1}$, they should have lifetimes of roughly 10^4 yr . Less than 1% of an OB star's lifetime of a few megayears should therefore be spent within an UCHR, so the same fraction of OB stars should now lie within UCHRs. However, Wood & Churchwell (1989) surveyed UCHRs and found numbers in our Galaxy consistent with over 10% of OB stars being surrounded by them, or equivalently, lifetimes $> 10^5 \text{ yr}$.

A number of explanations have been proposed for this lifetime problem, including thermal pressure confinement in cloud cores, ram pressure confinement by infall or bow shocks, champagne flows, disk evaporation, and mass-loaded stellar winds (see Churchwell 1999). Several of these explanations have basic problems that suggest they likely cannot explain the lifetime problem.

Confinement by thermal pressure of the surrounding molecular gas requires pressures of $P/k \sim 10^8\text{--}10^9 \text{ cm}^{-3} \text{ K}$ (De Pree, Rodríguez, & Goss 1995; García-Segura & Franco 1996). At typical molecular cloud temperatures of $10\text{--}100 \text{ K}$, this implies densities $n > 10^6 \text{ cm}^{-3}$. However, the Jeans (1902) mass

$$M_J = \left(\frac{4\pi\rho}{3}\right)^{-1/2} \left(\frac{5kT}{2G\mu}\right)^{3/2} = 6.1 \text{ M}_\odot \left(\frac{n}{10^6 \text{ cm}^{-3}}\right)^{-1/2} \left(\frac{T}{100 \text{ K}}\right)^{3/2}, \quad (1)$$

where we have assumed a mean mass per particle $\mu = 3.87 \times 10^{-24} \text{ cm}^{-3}$ appropriate for fully molecular gas with one helium atom for every ten hydrogen nuclei. Therefore cores massive enough to form OB stars contain multiple Jeans masses and are thus very likely to be freely collapsing (e.g. Mac Low & Klessen 2004). The free-fall time

$$t_{\text{ff}} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} = (3.4 \times 10^4 \text{ yr}) \left(\frac{n}{10^6 \text{ cm}^{-3}}\right)^{-1/2}. \quad (2)$$

Typical lifetimes of $> 10^5 \text{ yr}$ would thus require massive cores to last $> 3t_{\text{ff}}$ at the hypothesized densities, rather than dynamically collapsing. Although these high pressures are indeed observed, they are unlikely to occur in objects with lifetimes long enough to solve the problem. Xie et al. (1996) instead proposed a variation on this theme: confinement by turbulent rather than thermal pressure. However, turbulent motions decay quickly, with a characteristic timescale of less than a free-fall time under molecular cloud conditions (Stone, Ostriker, & Gammie 1998; Mac Low 1999). Turbulent pressure would thus have to be continuously replenished to maintain confinement for multiple free-fall times, which would be difficult at such high densities and small scales.

Another option is ram pressure confinement of UCHRs by infall of surrounding gas. However, this is unstable for two different physical reasons. First, the density and photon flux will follow different power laws in a gravitationally infalling region ionized from within, so they can never balance each other in stable equilibrium (Yorke 1986; Hollenbach et al. 1994). Either the ionized region will expand, or the infall will smother the ionizing source. Second, the situation is Rayleigh-Taylor unstable, as this option requires the rarefied, ionized gas of the UCHR to support the infalling, dense gas.

Bow shock models (Van Buren et al. 1990; Mac Low et al. 1991; Arthur & Hoare 2006) require high values of ram pressure $P_{ram} \propto nv_*^2$. At $n = 10^5 \text{ cm}^{-3}$, a velocity of $\sim 10 \text{ km s}^{-1}$ is required (Van Buren et al. 1990). A star moving at such a high velocity in a straight line would travel a parsec over the supposed UCHR lifetime of 10^5 yr , requiring a uniform-density region of mass $> 5 \times 10^3 M_\odot$ for confinement. As collapse would occur on the same timescale, more mass would actually be required to solve the lifetime problem.

Expansion of an H II region in a density gradient can drive supersonic champagne flows down steep enough gradients (Tenorio-Tagle 1979). Two-dimensional models first studied expansion across sharp density discontinuities (Bodenheimer, Tenorio-Tagle, & Yorke 1979), but then examined other configurations such as freely-collapsing cloud cores (Yorke et al. 1982), clouds with power-law density gradients in spherical (Franco, Tenorio-Tagle, & Bodenheimer 1990), and cylindrical (García-Segura & Franco 1996) configurations, and exponential density gradients (Arthur & Hoare 2006). Stellar wind combined with a champagne flow down a continuous gradient was also modeled by Arthur & Hoare (2006). This model does fit well the observed velocity structure in some cometary UCHRs such as G29.96–0.02. However, these models face the same timescale problem as thermal pressure confinement models: regions dense enough to explain the observations are gravitationally unstable, and collapse on short timescales.

Another class of models relies on mass-loaded stellar winds to reproduce the observed properties of UCHRs (Dyson, Williams, & Redman 1995; Redman, Williams, & Dyson 1996; Williams, Dyson, & Redman 1996; Lizano et al. 1996). In these models, an expanding stellar wind entrains a distribution of small, self-gravitating, pressure-confined clumps that take substantial time to evaporate. These models can reproduce many of the basic features of the observations including some line profiles (Dyson et al. 1995), core-halo, shell (Redman et al. 1996), and cometary and bipolar shapes (Redman, Williams, & Dyson 1998), but at the cost of requiring an arbitrary distribution of pre-existing clumps that cannot be self-consistently predicted.

Finally, Mac Low et al. (2007) examines the expansion of H II regions into turbulent, self-gravitating gas. At densities high enough for massive stars to form, the expanding shell driven by newly ionized gas quickly becomes gravitationally unstable (Voit 1988; Mac Low & Norman 1993), collapsing even more promptly than the surrounding gas. These regions of secondary collapse in the shell may be externally ionized to form objects with the properties of UCHRs. As the shell expands to larger sizes, new regions can form, extending the lifetime during which UCHRs remain visible well beyond the expansion time of the original H II region. Some combination of secondary collapse and disk evaporation appears to me most likely to ultimately be the solution to the UCHR lifetime problem.

2. Large Scale Feedback

The radiation, winds, and supernovae from massive stars also influence their galactic environment. Two questions of current interest are: 1) Can compression driven by feedback trigger further star formation with an efficiency above

unity, allowing self-propagating star formation? 2) Can any of these forms of feedback support molecular clouds for many dynamical times, reducing their star formation efficiency per unit free-fall time, or, alternatively, giving a negative triggering efficiency?

Stellar feedback certainly produces compressive motions. The suggestion that expanding H II regions might compress surrounding gas and trigger further massive star formation was first made by Elmegreen & Lada (1977) and Elmegreen & Elmegreen (1978). They assumed that turbulent velocities in the shell would be of the same order as the expansion velocity. Ostriker & Cowie (1981) and Vishniac (1983) assumed, on the other hand, that the turbulent velocities in the shell would only be transonic. This latter assumption was supported by analytic work by Voit (1988) and numerical work by Mac Low & Norman (1993). The operation of this mechanism in three-dimensional simulations of expansion into a turbulent medium is described by Dale et al. (2005) using a smoothed particle hydrodynamics code and by Mac Low et al. (2007) using the ZEUS-MP grid code (Norman 2000). These models show that the clumpiness of the turbulent medium allows the ionization front to blow out of the collapsing core, while the denser regions resist ionization and continue to collapse. Neither model finds evidence for efficient triggering—indeed in the more global model of Dale et al. (2005) there is some evidence for negative feedback—fewer stars forming in the presence of the H II region than otherwise. Dale, Clark, & Bonnell (2007) extended this result by examining an externally ionized collapsing core, and found rather inefficient triggering in that case as well. These low or negative triggering efficiencies occur when the acceleration and stirring of the gas by a shock wave expanding into a clumpy medium dominates over direct compression.

Supernovae compress gas on even larger scales than H II regions, so they are also often invoked as triggering agents. Joung & Mac Low (2006) simulated supernova-driven turbulence using the Flash adaptive mesh refinement code Fryxell et al. (2000) on a grid covering 500 pc on a side in the plane and 5 kpc up and down vertically, with 2 pc resolution within 200 pc of the plane. When the galactic fountain flow had reached a steady state, the density, pressure, and velocity dispersion of the gas in two-zone cubes was compared to the turbulent Jeans criterion for collapse, to measure the expected star formation rate in the flow. If a generous local star formation efficiency of 30% is assumed for the unstable gas, they find that the resulting star formation rate is a full order of magnitude below the value required to generate the input supernova rate.

These results on triggering by ionizing radiation and supernova explosions taken together suggest that triggering does indeed occur, but that it is only a 10% effect rather than the primary mechanism controlling star formation (although it may be more important than this for massive star formation in particular). A recent observational test supports this result. Mizuno et al. (2007) used the NANTEN telescope to survey dense molecular gas interacting with 23 southern H II regions within 4 kpc of the Sun. The detected clouds were divided into regions adjacent or not adjacent to the H II regions. The adjacent regions indeed contained more protostellar objects, and ones with significantly higher far-infrared luminosities luminous protostellar objects. However, when the effect is integrated over the galaxy, it appears to be only a 10–30% effect.

If triggering is not that effective, is feedback good at the converse—supporting molecular clouds against collapse? The question of how long-lived molecular clouds remains very controversial, with answers ranging over an order of magnitude from one to as long as ten free-fall times. Long time scales are argued for on the basis of either magnetic (Mouschovias, Tassis, & Kunz 2006) or turbulent (Krumholz, Matzner, & McKee 2006) support, while short time scales depend on sweeping by shock compression (Ballesteros-Paredes, J. Hartmann, L., Vázquez-Semadeni, E. 1999, ApJ 1999; Hartmann, Ballesteros-Paredes, & Bergin 2001; Padoan et al. 2007) or direct gravitational instability and collapse (Li, Mac Low, & Klessen 2005; Elmegreen 2007).

Matzner (2002) argued that turbulent support of molecular clouds can be maintained by H II region expansion within the clouds, for clouds with a mass greater than $3.7 \times 10^5 M_\odot$. His analysis suggests that such large clouds reach a balance between energy injection and decay in a turbulent cascade. Krumholz, Matzner, & McKee (2006) used this analysis and made the additional assumption that giant molecular clouds are spherical objects with homologous, power-law distributions of density, energy injection, and other relevant quantities. Using a star formation law (Krumholz & McKee 2005) derived from the turbulent collapse models of Vázquez-Semadeni, Ballesteros-Paredes, & Klessen (2003), they find that large molecular clouds remain quasi-stable for as long as 20–40 Myr. Similar work was performed by Huff & Stahler (2007) in the context of the Orion Nebula Cluster.

However, Elmegreen (2007) reaches opposite conclusions working from almost the same assumptions. He argues that giant molecular clouds never have spherical, homologous shapes, but rather are filamentary objects containing quasi-spherical cluster-forming cores of order $10^4 M_\odot$. In his picture, these dense cores are dispersed by H II region expansion within 2–4 Myr, but magnetically supported envelopes that are not participating in gravitational collapse may indeed survive for much longer.

The observational evidence has not yet clarified the picture either. A study by Fukui’s group of the associations between young clusters, H II regions, and molecular gas observed by NANTEN, reported in Blitz et al. (2006), suggests that GMCs remain without visible H II regions for about 7 Myr—though Gruendl & Chu (2007) used *Spitzer* to show that they do have young stellar objects. About another 14 Myr passes before visible clusters appear, and then 6 Myr remain before the molecular gas is cleared away, for a total of as much as 27 Myr. They also note that the average mass of the observed objects increases with the stage of life. They interpret this as suggesting continuing accretion onto the clouds over their lifetimes.

On the other hand, Tamburro et al. (2007) have used global imaging of nearby galaxies from the *Spitzer* IR Nearby Galaxies Survey (Kennicutt et al. 2003) and The H I Nearby Galaxy Survey (Walter et al. 2007) to measure the average delay between the peak of H I emission and the peak of star formation as measured by $24 \mu\text{m}$ emission from warm dust in regions of massive star formation. They find values of 2–4 Myr for the delay, with no values above 6 Myr in their sample of over 20 galaxies.

While the peak of $24 \mu\text{m}$ emission does not yield the total lifetime of the molecular clouds, it does measure the period of strongest star formation. The

results of Tamburro et al. (2007) suggest that star formation begins promptly and strongly within a few million years of the onset of gravitational instability as traced by H I emission. The timescales cited by Blitz et al. (2006) make no reference to the strength of star formation during any particular period, though, so perhaps the two observations are consistent with the theoretical picture of cloud support by H II region expansion: if clouds collapse promptly, forming many young stars, the result could be well supported clouds with low ongoing star formation efficiency. Investigation of this scenario looks like a fruitful direction for further research.

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